SUPERCONDUCTING ACCELERATOR MAGNET COOLING SYSTEM

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Summary

A cryogenic system has been designed for cooling ~1000 superconducting magnets associated with the proposed "energy-doubler" at the National Accelerator Laboratory. This paper reports on design parameters, cooling concepts, heat transfer and pressure drops. Even though in final design changes are anticipated, the attempt in this work is to complete a refrigeration design which would accomplish the cooling necessary for the energy doubler magnets.

Design Parameters

From the time that R.R.Wilson[1] first proposed to increase the energy of the 200/500 BeV NAL accelerator by the incorporation of a separate superconducting ring of magnets in the 6000 meter long tunnel, emphasis has been placed on utilizing existing facilities such as the main ring tunnel, the service buildings, the connecting passages and the installed utilities. Also used is the concept of self-sufficient independent modules with the interconnection between modules limited to a vacuum pipe for the proton beams.

Since there are 24 service buildings located at approximately 240 meter intervals around the accelerator, and these buildings are only partly occupied with equipment, we have considered locating the refrigeration equipment in these buildings and have investigated the feasibility that each refrigerator service at least 240 meters of energy doubler magnets. Depending on refrigeration requirements and the size of equipment, it may be feasible to reduce the number of refrigerators to 12.

Other design parameters chosen at the start of the project were the following:

1) The magnets will be constructed with warm iron located outside the vacuum shell of the magnet dewar.

2) Total refrigeration requirements were selected to be 5 watts per meter. This number was chosen on the basis of information given in papers by P. F. Smith and Bronca et al. [2, 3].

In particular, in the third reference for a rise time of 33 s the total losses were given as 4.4 watts/meter for a warm iron magnet similar to energy doubler magnets. The static losses were estimated as 3.5 watts/meter, leaving 0.9 watts/meter for the ac losses. We, therefore, began our studies by using the following division of the refrigeration loads:

AC losses in the magnet:	1 watt/meter
Heat gain through insulation and supports of the magnet:	2 watts/meter
Miscellaneous:	2 watts/meter

The total amount of refrigeration to be provided served primarily as a guide in order to be able to develop concepts for the refrigeration system.

Cooling Concepts

One of the most difficult problems of the cryogenic design of a superconducting accelerator is the transport of refrigeration from a central refrigerator or liquefier to the magnets located at great distances. A basic system might consist of transfer lines carrying liquid and gas, running in parallel with the accelerator. Examination of this system leads quickly to the conclusion that the cost of such a system is very high. Location of small refrigerators at short intervals eliminates the transfer line system. Again, the cost of such a system is high and operational reliability probably is low.

Since the magnets form a completely closed loop, it seems desirable to use the magnet system itself as the transport system for the cryogenic fluids. Reference 4 describes a system in which supercritical helium is pumped around the accelerator loop.[4] Heat exchangers and pumps located at the service buildings remove heat from the liquid. The system depends on the specific heat of supercritical helium for removal of heat from the magnet system. This requires a temperature rise along the path of fluid flow. If the temperature rise is to be kept to a low value, flow rates need to be high. This, in turn, means increased pressure drop and a relatively large amount of heat generated by the pumps moving the supercritical helium. This increases the size and cost of the helium refrigerators. The concept was abandoned because it is difficult to isolate parts of the system in case of magnet failure. Also, the temperature rise of the liquid helium flowing through the magnets limits superconductor capability at the warm end and results in rather short distances between adjacent refrigerators.

Figure 1 shows the schematic flow arrangement of a module of the magnet system, which eliminates the disadvantage of a rising liquid helium temperature along the path of flow. A helium pump compresses liquid helium from a liquid helium reservoir of the refrigerator. The supercritical helium flows through and around the windings of the magnets over a distance of some 120 meters. At the end of the path (halfway between service buildings), the liquid helium flows through a valve and becomes boiling liquid helium. The boiling helium is returned through an annular space around the magnet vessel to the liquid reservoir of the refrigerator. A fraction of the liquid helium is vaporized through heat transfer. Part of the heat transfer takes

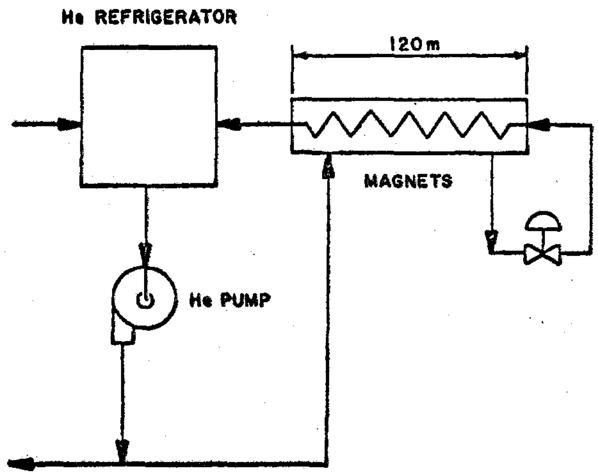

FIG. 1

place between the supercritical helium in the magnet vessel and the boiling helium in the annular space. Heat arriving from the environ ment also vaporizes part of the low pressure helium.

The system of Figure 1 has a number of interesting features, as follows:

1) With a large surface area for heat transfer between supercritical and boiling helium, it is possible to maintain a constant temperature in the magnet vessels independent of distance from the refrigerator.

2) The heat flowing in from the warm environment never enters the supercritical helium system of the magnets.

3) It is possible to reduce the temperature of the magnets by reducing the pressure of the boiling liquid helium. For instance, maintaining a pressure of .5 atm in the boiling helium system, a boiling temperature of 3.55°K is realized. With good heat transfer a magnet temperature of 3.7 to 3.8°K may be obtained.

The combination of 1) and 2) reduces the flow required for maintenance of a constant temperature to a minimum. This minimum is determined by the total heat flux to the 4°K temperature system divided by the heat of vaporization of liquid helium.

Figure 2 shows a cross section of a bending magnet in which the described flow system is incorporated. Figure 2 also shows a thermal shield which surrounds the 4°K system and which is maintained at 15-20°K. Heat is removed from the shield by helium gas (at approximately 20 atm) flowing from the refrigerator through 2 tubes. The helium gas is returned through the other 2 tubes to the refrigerator. The tubes are thermally fastened to the shield. The helium of the cooled shield removes the bulk of the heat entering from the warm environment. This reduces the required flow rate of 4°K helium and improves the thermodynamic efficiency of the cryogenic system markedly.

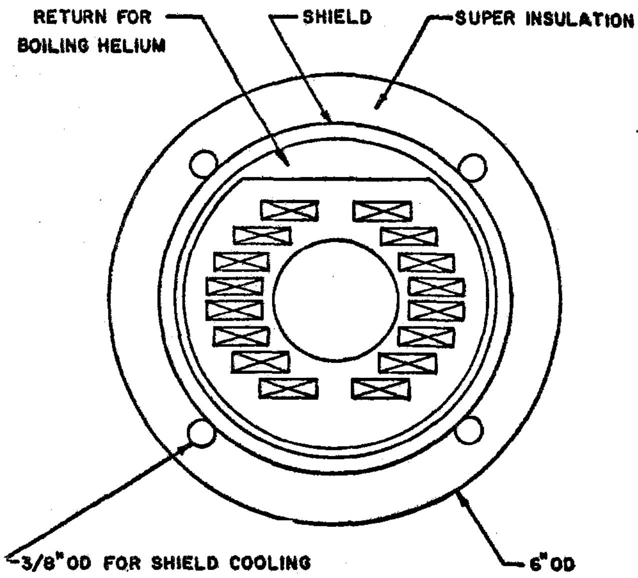

FIG. 2

The proposed cryogenic system of Figures 1 and 2 has been examined in more detail to determine whether the advantages as described can be realized in practice.

Heat Transfer

In order to maintain the temperature of the magnets at the lowest possible constant temperature, heat needs to be transferred efficiently from the magnet windings to the supercritical helium and then from the supercritical helium to the boiling helium.

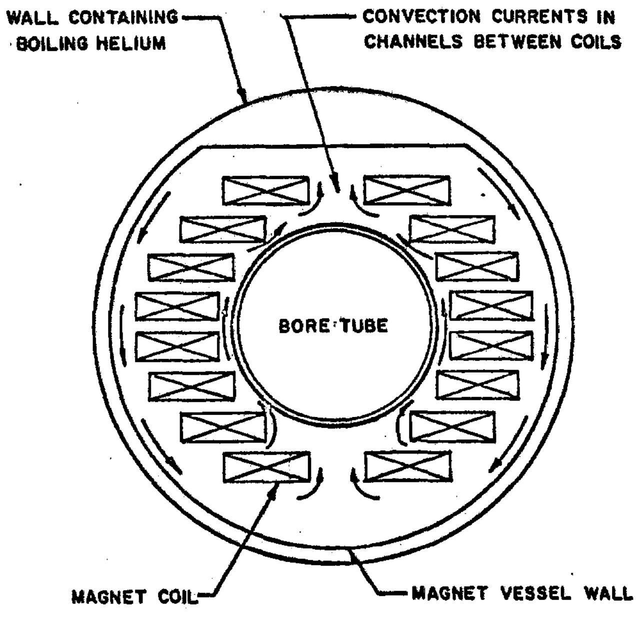

FIG. 3

Figure 3 shows how heat is removed from the magnet windings by the supercritical helium present in cooling channels between the windings. As soon as heat is added to the helium from the windings, its density decreases.

On the other hand, helium located outside the windings is cooled by the boiling liquid helium in the annulus surrounding the magnet vessel. Its density increases. The change in density of the two columns of helium sets up convection currents and helium starts to circulate. Calculations have been made to determine the flow rates obtainable as a function of channel dimensions and temperature rise of the fluid flowing through the channels in the windings. If the heat to be removed is of the order of 1 watt per meter of magnet length, the temperature of the windings may be maintained at a temperature .1 to .2°K above the bulk fluid temperature outside the windings. The bulk fluid outside the magnet windings is cooled by the boiling liquid helium surrounding the magnet vessel. The heat transfer coefficients have been determined for the configuration shown in Figure 2. Although the wall of the magnet vessel is made of stainless steel, the surface area available for heat transfer is so large that the temperature difference between the boiling liquid and supercritical helium can be maintained at .025°K. The mass flow rate in the boiling liquid helium channel is an important parameter which determines the type of flow in this channel. Reference 5 discusses the type of flow which may be expected in a channel when a mixture of liquid and gas is present.[5] Figure 4 is a plot of various types of flow possible as a function of two parameters determined by fluid properties, fraction of liquid and gas, and dimensions. For good heat transfer it is necessary that the type of flow in the channel carrying the two-phase helium is bubble or froth. The two lines (flow rates of 115 and 314 lb/h) indicate that in vaporizing approximately 50% of the liquid helium in passing through 120 meters of channel, the type of flow is always bubble or froth.

Pressure Drop

After the minimum flow rate required for satisfactory heat transfer has been determined, pressure drop in the flow system may be determined. The dimensions as shown in Figure 2 were used with a flow rate as determined for maintenance of satisfactory heat transfer. Table I shows the pressure drop of the high pressure flow in the magnet vessel and the boiling helium in the annulus surrounding the magnet vessel for a distance of 120 meters.

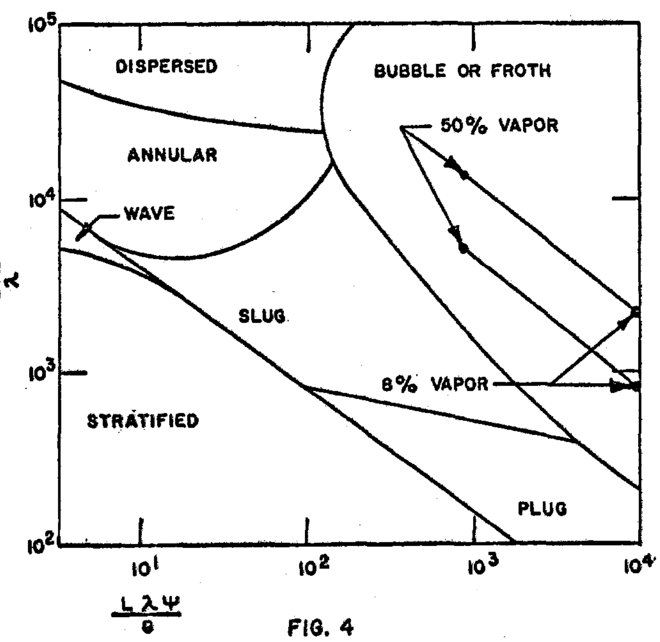

FIG. 4

TABLE I

Pressure Drop of Supercritical and Boiling Helium Streams

Flow rate of liquid helium:	115 lb/h
Pressure drop of supercritical helium:	1.65 psig
Pressure drop of boiling liquid helium:	.56 psig

Refrigerator Requirements

Magnet supports and insulation have been determined with sufficient detail to permit a reasonably accurate estimate of refrigerator requirements. Table II shows the various heat loads at the 4 and 20°K temperature level for a refrigerator serving a module with a total length of 240 meters.

TABLE II

Refrigerator Requirements

Refrigeration at 20°K:		650 watts
Refrigeration at 4.4°K:		
Pump work	120	
A-C heat in magnets	240	
Heat from 20°K environment	20	
Miscellaneous	60	
		440 watts
Liquid helium for leads:		25 l/h

References

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